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INFRASTRUCTURE AND MAINTENANCE OF WATER QUALITY

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16. ABSTRACT

Concern over maintenance of water quality in distribution systems and a growing awareness of the apparent decay of America's infrastructure has motivated EPA's Drinking Water Research Division to sponsor a series of projects dealing with the repair and rehabilitation of drinking water distribution systems. The quality of a public water supply, although acceptable when it leaves the treatment plant, may deteriorate before it reaches the user. This paper analyzes the various factors that influence repair and replacement decisions in water distributinn systems and the problems surrounding maintenance of water quality.

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INFRASTRUCTURE AND MAINTENANCE OF WATER QUALITY

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INTRODUCTION

The quality of a public water supply although acceptable when it leaves the treatment plant, may deteriorate before it reaches the user. Deteriorations may be caused by either chemical or biological transformations or by a loss of system integrity. Living organisms and nutrients may enter the distribution network with the raw water, be produced during the treatment processes, or enter through sources such as leaks, cross-connections, etc. However, microbial growth may occur in the network, in the water, and on the walls (biofilms), and microbial cells may be trapped in mineral deposits (tubercles). Growth occurs at the expense of nutrients in the water. The potential for growth in the pipe network is greatly enhanced if disinfectant residuals cannot be maintained throughout the extent of the distribution system. Consequently, the phenomenon of "regrowth" may be observed in the distribution system despite treatment and disinfection at the treatment plant to eliminate such microbial activity.[1]

Concern over maintenance of water quality in distribution systems and a growing awareness of the apparent decay of America's infrastructure has motivated EPA's Drinking Water Research Division to sponsor a series of projects dealing with the repair and rehabilitation of drinking water distribution systems.

Infrastructure generally means the roads, bridges, sewers, water systems, rail systems, and mass transit, which routinely supply services

to the urbanized population of the United States. This decay is probably most accute in the older industrial cities, but many other communities are expressing concern over the infrastructure issue as well. Cities and communities, large and small, rural and urban, are all feeling the pressure of clogged highways and capacity limitations. In water supply, assessing the infrastructure problem is particularly difficult because the investment is usually long lived and the distribution pipes are buried.

The exterior signs of street repair and traffic disruption associated with water distribution maintenance can be seen in almost any municipality in the United States. These scenes are typical of the exterior manifestation of the infrastructure problem. Internally, the situation may be one of heavy tubercules attached to the pipe wall reducing the original diameter of some very large pipes to very small orifices, resulting in tremendous increases in pressure to pump water. These tubercules may provide a haven for potentially pathogenic bacteria, and contribute to accelerated corrosion as well.

This paper will attempt to analyze the various factors that influence repair and replacement decisions in water distribution systems and the problems surrounding maintenance of water quality. In addition to a retrospective analysis of data from two case study utilities, current efforts related to the analyses of repair and replacement in drinking water will also be discussed.

DRINKING WATER QUALITY AND ECONOMICS

The Safe Drinking Water Act of 1974 mandates that EPA be concerned with the supply of potable water to the consumer.[2] Historically, most regulatory emphasis has been focused on the treatment function although it is well known that the water delivery system itself can cause significant deterioration in water quality. There are many mechanisms that can introduce bacteria into the drinking water. These include: open reservoirs; enclosed reservoirs to which chlorine is not added occasionally; new construction which may disturb the existing system; main breaks which may become an increasing problem as distribution systems age; cross-connections improperly installed which cause back syphonage and back pressure; dead-ends in mains which cause stagnant water; and living organisms in mains which protect bacteria but which, when disturbed, may release bacteria into the drinking water.[3] The early history of drinking water systems is repleat with examples of dramatic reduction of waterborne disease outbreaks associated with the adoption of water treatment for surface water supplies.

Distribution system deficiencies actually account for the highest

percent of all waterborne outbreaks recorded in the United States. The interupted disinfection of ground water accounts for most of the cases. Table 1 illustrates the problems of distribution deficiencies. In the period between 1946 and 1970, we can see that there were 59 outbreaks and 4,736 reported cases.[4] In the period from 1971 to 1980, there were 43 outbreaks, but 8,702 cases, so that problems associated with distribution deficiencies account for roughly one-seventh of all the outbreaks, and one-tenth of all cases. Although this represents a relatively low number of cases, as mains continue to age, awareness of the problem increases, and reporting of cases improves, there will undoubtedly be many more outbreaks recognized in the future as demonstrated by comparing 43 outbreaks between 1970 and 1980 and only 59 in the preceding 24 years.

Of growing concern is the increasing number of reported incidents in which the occurance of coliform bacteria has been documented in the presence of free chlorine residuals.[5] In one reported case routine bacteriologic monitoring of a water distribution system serving 350,000 people in Connecticut revealed elevated total coliform counts. The mean counts were 12.1 coliforms per 100 ml as measured against a standard 1 coliform per 100 ml. The distribution system received water from four reservoir systems and five well fields. Water from three of the reservoir systems was filtered and chlorinated. Water from the other reservoir and from the well fields was chlorinated but not filtered. Free chlorine residuals were maintained at 0.6-1.0 mg/l in treatment effluents from surface sources and 0.2-0.4 mg/l at the well fields and ranged from 0.2 mg/l to 0.5 mg/l at points in the distribution system.

The incident is consistent with the fact that water distribution systems normally contain living micro-organisms and nutrients that may enter a system with raw water during treatment failures or from sources such as leaks, cross-connections, and back-flows. Bacterial growth may occur at or near the pipe surfaces (biofilms), the interface of suspended particulates, and within the water itself. Factors that influence bacterial growth include water temperature, flow rate, and chlorination. The bacteria commonly found in biofilms grow on minimal nutrients and are able to encapsulate or develop a gelatinous slime that protects them from the effects of chlorine.

The data from the Connecticut investigation were consistent with the hypothesis that the elevated total coliform counts were due to the sloughing of coliform bacteria that had accumulated within a biofilm on inner pipe surfaces. Water quality problems caused by the bacterial colonization of distribution systems are probably much more common than reported. The formation of the biofilm will contribute to the destruction of the pipe wall itself and result in loss of hydraulic capacity.

There are many important interactions between cost and water quality. For example, consider the example of long-term corrosion of older mains which can result in tuberculation, thereby reducing carrying capacity. The reduction in carrying capacity require increasing

investments in power and pumping, thereby causing a trade-off between the reduction in hydraulic capacity and the increased O & M expenses to get water from one point to another. In addition, the bacterial growth within tubercules may cause a potential health problem. Tuberculation also weakens the main by reducing the wall thickness. This reduction in carrying capacity and reduction in strength can cause increased pumping costs and increased breakage and repair costs, and of course, increase the cost of water delivery.

ECONOMICS OF DRINKING WATER

Water supply is an important economic consideration. Capital investment in water supply has averaged 3.3 billion dollars a year for the last five years, and annual operating and maintenance expenses amount to roughly 3 billion dollars a year.[6]

Table 2 shows the relative costs associated with the various water supply functions. As we can see from Table 2, transmission and distribution account for the largest percentage of capital investment and a significant portion of the operating cost investment. The distribution system often involves 80% of the total expenditure in drinking water systems.[7]

CASE STUDY ANALYSIS

In the following section a retrospective analysis of the break history of two case study utilities will be presented. The case studies not only provided insight into main break occurrences and utility operation, but also contributed to the development of tools enabling the incorporation of water quality considerations into a cohesive analytical package. A utility should have a data base management system that includes break, network, and water quality data to facilitate better long and short term management. It is not readily apparent to all that water characteristics can cause breaks and in turn, these main breaks can further effect water quality in different ways. Table 3 describes the utilities studied.

Using historical data, a time series evaluation of the repair and replacement records of both utilities was made. Analysis of the data showed that only a very few of the pipes examined caused most of the maintenance problems. In fact, most of the pipes have no maintenance events associated with them at all, even after very long periods of time. Table 4 lists by pipe diameter, the percentage of pipes in the network as considered in the case analysis versus the percentage of pipes in the actual distribution system for both utilities.

Analysis of the pipe break data revealed that after 45 years for Utility 1, 70% of the pipes examined had no maintenance events and over 80% of the pipes in Utility 2 had no maintenance events.

Life expectancy curves were developed for each utility. A life expectancy curve defines the condition that given a pipe X years old, without having had an event, how long it would be expected to last before it experiences an event for the first time.

The life expectancy analysis for Utility 2 was much more optimistic than for Utility 1. After 40 years in Utility 2, one would expect a pipe to last an additional five to six years before experiencing an event. After 40 years, in Utility 1, one might expect a pipe to last another year before having a repair event.

In addition to looking at general historical records, an evaluation of the spatial distribution of maintenance events was made in order to identify areas of high repair intensity. Each of the utility service areas was subdivided into sub-areas in order to study spatial variations in repair rates. In Utility 1, for example, repair rates varied from 0 per mile to 30 per mile. In Utility 2 over various regions, the time to the first break varied from 11 years with a standard deviation of 11 years, to a time of first repair of 27 years with a standard deviation of 21 years.

From examination of the individual and aggregate event records as mentioned earlier, it appears that there are two time periods associated with maintenance events for individual pipes. Period one is from installation to the first repair event. This period seems to occur almost at random for individual pipes, but can be characterized by a mean time to first event for a given area. The period between installation and the first repair could be considered a latency period before the first event occurs. The second period occurs after the first event and is a period in which we might expect increasing numbers of repairs or maintenance events, given that the first event has occurred. Generally after each event the time to the next event becomes increasingly short. Therefore, if a pipe has had one repair event the probability of another is quite high. Figures 1 and 2 illustrate this pattern for both utilities.

STATISTICAL ANALYSIS

A major problem in performing a statistical analysis was the definition of a "unit of analysis." As mentioned earlier, lengths of pipe for analysis where chosen based on sections of the same diameter or material. This resulted in length of pipe in one utility from a few hundred to 14,000 feet. Methods for surmounting this problem in actual data collection efforts are discussed later.

An attempt was made to evaluate the various factors that influence the frequency of repair events. Figure 3 provides a graphical illustration as to how age and length of pipe might affect the event rate for Utility 2. There is obviously a relationship between the number of repair events and the average age of the system, as well as the average length of pipes in the system. Both age, possibly an indicator of internal and external corrosion, and length, which might relate to the type of pipe or compression problems in the system itself, are related to this increasing number of repair events.

In order to quantify some of these relationships, a general regression analysis was performed. Although, as might be expected, results were somewhat variable, a categorical variable indicating period of installation was significant in both equations. The categorical variable was defined according to the date of pipe installation. In this case an installation cutoff of 1960 was assumed for the following reason: before 1960 most of the system was thick wall cast pipe, after 1960 it was thinner walled ductile iron pipe. The thinner wall pipe may be breaking at an increasing rate as compared to the thicker wall pipe installed before that date.

Examination of the individual repair event history is critical. Even in high maintenance event areas there is a wide variation among the individual pipes and their maintenance event records. Figure 4 displays the typical kinds of repair event records one might see even in adjacent pipes. The example pipe in Utility 1 has a very high event rate, whereas the Utility 2 pipe depicts a subsection in which the first event occurred after approximately 30 years and with the subsequent and additional breaks occurring after another 20 years. Based on these highly variable patterns optimal repair and replacement strategies are examined in the following section.

OPTIMAL REPAIR AND REPLACEMENT

Several investigators have examined issues related to repair and replacement of water distribution pipes.[8,9,10] In order to illustrate optimal repair and replacement strategies, a 25 year repair record for a pipe from Utility 1 was used. Two repair histories were hypothesized beyond the end of the actual record date. One pattern (scenario 1) assumes a constant repair record per year, and the other (scenario 2) assumes an exponentially increasing rate. A weighted average cost function was used to calculate the optimal replacement time.[11] The two patterns appended to the 25 year, actual records are shown in Figure 5. Scenario 1 assumes a constant break rate in the future, and scenario 2 assumes an exponentially increasing rate.

An average weighted cost function as given by equation 1 was used, where A is the initial cost, C_i is the cost incurred in each period, and X^{i-1} is the discount factor applicable in each respective period. The average weighted cost was evaluated to find the minimum cost replacement point as shown in the following equation:

$$C_{av} = \frac{A + C_i X^{i-1}}{X^{i-1}} \qquad (1)$$

where

C_{av} = average weighted cost
A = initial cost
X^{i-1} = discount factor applicable in respective period
C_i = cost incurred in each period

Figure 6 shows the plot of this function. The initial cost "A" is assumed to be 200,000 dollars with "C_i" being 2,000 dollars per maintenance event in this scenario. The solid line shows the minimum replacement cost for the actual break rate through the first 25 years. The scenario 2 line is based on an increasing event rate of two additional events per year after 25 years. Scenario 1 is based on a constant break rate of two events per year after 25 years. The minimum cost point occurs at approximately 30 years for scenario 2 but no minimum occurs for scenario 1.

Because an exponentially increasing break rate is unlikely, one can see from this analysis it is unlikely that a pipe would be replaced based on the direct cost of maintenance events alone. It also illustrates how important maintenance event patterns are in making decisions to repair or replace pipe sections.

Walski has prepared an extensive summary of data relating to the cost of water distribution system infrastructure rehabilitation, repair and replacement.[12]

DATA BASE DEVELOPMENT

It is clear from the previous analysis that a key factor in making proper repair and replacement decisions with regard to drinking water infrastructure issues is adequate data collection and analysis. Traditionally, most water utilities repair or replace mains as the situation seems to dictate with little long term or integrated planning. Although most utilities possess large amounts of data, it is rarely in a form easily accessible or useful in providing reliability estimates, analysis, or developing decision-making criteria for repair or rehabili-

tation. This section will deal with techniques being developed by the Drinking Water Research Division of the EPA to enhance and organize data collection efforts for pipe repair, replacement and rehabilitation decisions that will in turn have a sizeable impact on the cost and quality of water reaching the tap.

DATA CENTERED APPROACH

Each utility is unique with its own set of records, distribution system problems and goals in developing management tools. The use of a data base centered approach linking the distribution network spatially with a "geo-code" system facilitates multiple tasks. The key to drinking water supply delivery analysis is the performance of reliability assessments.[13] The critical component of an inventory and water main condition assessment is the geo-spatial coding of data, thus providing a common reference system. The Louisville, Kentucky, Cincinnati, Ohio and Kenosha, Wisconsin Water Works are undertaking projects which include (1) an overall description of the system (connectivity, physical characteristics, etc.), (2) structural integrity, (3) quality of service and level of usage, and (4) safety. Each link, node, break and customer complaint can be uniquely identified by its location in State Plane Coordinates and/or the United States Bureau of Census DIME File code. In this manner, a variety of data such as soil-type, land use, traffic load, operating pressure, elevation, etc., can be assessed. Reliability analyses using any model can also be integrated into the framework since the network is already specified. Thus, "reliability" analyses need no longer be simply simulations calculated by a hydraulic model, but can also incorporate socio-economic variables. The ability of a utility to anticipate, detect, repair, rehabilitate, reconstruct or replace water supply delivery components is enhanced by the geo-spatial coding of data which provides a common reference system.

DATA COLLECTION

Data collection, or more appropriately, data organization within most utilities is a painstaking process. The data are already present, usually in file cabinets, but of limited use in this form. The first step in developing a useful data base is to identify links and nodes for the system. A link is a stretch of main between two junctions and should be much shorter than what is typically used in the modeling of transmission units. A junction or node can be located at the intersection of pipes, change in diameter, end of a line, significant change of alignment, division gates, or valves. Useful information for each link should include both nodes, pressure, installation date, diameter, material, length, etc. Maintenance information should include specific street address of maintenance event, type of problem (main line leak, joint leak), depth, type of action taken, local environmental conditions, plus any other available information the utility desires.

DATA MANAGEMENT

Data entry, storage, retrieval and file manipulation using a spatial orientation on a microcomputer are effectively handled by a "relational" data base management system. In this type of data base, data are organized into a series of interrelated two dimensional tables. Such a system is easy to construct. Figure 7 illustrates how drinking water distribution system network data can be organized in a relational form. Information from any table can be used in conjunction with retrievals through relationships shown by the dotted line.

DATA ANALYSIS

Microcomputer data base management systems vary in capabilities but generally are able to produce descriptive statistics, spreadsheets, graphics and English-like queries. A very useful aspect of a relational data base management system is its sorting capability. Sorting data by those mains with multiple maintenance events within a range of geographic reference points can identify "hot spots" or pipes of similar characteristics that could then be flagged as priority items for action. If a mainframe computer or sophisticated statistical software is available, a data file can be created to meet the model or program requirements through the sorting mechanism. Thus, optimization techniques, hydraulic analyses, network reliability analyses, etc., can be performed without locking the data into a specific format only of use to one model.

EPA SPONSORED RESEARCH

In addition to the statistical analysis described earlier more formal models are being developed that utilize the data collection efforts described herein.

COX'S REGRESSION

In addition to general deterministic and regression approaches, probabilistic regression analyses were performed on Utility 1 and 2 pipe maintenance data in cooperation with MIT.[14] The approach combined in-depth descriptive and bivariate statistical analysis with the regression analysis procedure developed by Cox in 1972. The Cox regression model is a general failure prediction model which was applied to the water distribution data concerning pipes that have been maintenance events and also those pipes that have not had maintenance events. The Cox regression model determines the probability of a pipe experiencing a maintenance event (break, leak) at any given point in time as a function of certain direct or surrogate factors that appear to be correlated to the pipe break mechanism. One of the purposes of performing this regression analysis was to define the variables affecting the probability of maintenance events and to determine the relationship between them. The major variables identified to date affecting the

probability of pipe breaks include internal pipe pressure, land development covering the pipe, age of pipe at the time of the second break, installation period, and the number of previous breaks on the pipe.

Cox's regression model derives the probability of experiencing a break in each specific pipe rather than the expected number of breaks in a given year as determined using the general regression approach. The Cox model is thus particularly well suited to the prediction of maintenance events for systems with relatively infrequent breaks. Large mains tend to experience fewer breaks yet these breaks are of more extreme consequence. The prediction of these more consequential breaks is of great interest to utility management. The Cox regression model is designed to function on such pipes with relatively low probabilities of failure while several of the other deterministic regression models are less appropriate. The probability results from the Cox regression models can be directly used to prioritize maintenance actions. These results could also be combined with cost information associated with the different maintenance alternatives in order to rank pipes for maintenance strategies. This information is intended to be used as an aid to support the organization and preparation of water distribution maintenance plans and budgets.

CONDITION ASSESSMENT

The City of Philadelphia, working with the EPA and the American Water Works Research Foundation Association, has developed an assessment model that incorporates taking physical samples from pipes for which repairs have been made. The samples are tested metallurgically and characterized as to failure type. Soil samples are taken for resistivity measurements. Structural tests are made to relate the strength of the remaining pipe material to tension, compression and shear forces. The data are then incorporated into a Condition Assessment Model which will be used to estimate the structural condition of pipes given the projected locality and environmental conditions.

In addition to the specific work, a broader based data collection effort is being undertaken from five utilities to assess such specific characteristics as breakrate influenced by weather, management practices, etc.

QUALITY PREDICTION

In order to "tie" together the work being sponsored by the EPA in the area of main repair, rehabilitation and replacement, with quality issues, work is also being conducted in the area of water quality assessment and prediction within the distribution system. Figures 8 and 8A illustrate the various mechanisms associated with water quality deterioration

Various projects associated with water quality prediction are discussed in the following section.

WATER SUPPLY SIMULATION MODEL (WSSM)

The WSSM is based upon the concept of a water utility as a network overlaid upon a spatial distribution of supply and demand. The model explicitly deals with the relationship of delivered water costs to the service requirements of spatially and temporally distributed demand. The spatial representation is based on a characterization of the water supply system as a link-node network. It is assumed that water enters and leaves the system only at nodes, which represent treatment plants, junctions, demand locations, and storage tanks. Water is carried between and among nodes through connecting links. Costs are allocated to the various facilities and system components based on flow in the system.[15]

The WSSM requires that the system be described as a network of pipes, storage tanks, treatment plants, demands and other hydraulic elements. Information concerning the network is stored in a network data base, which also stores additional descriptive or calculated information about each element, such as size of pipe, geographic location of each demand often using state plan coordinates, population associated with a demand, connectivity of pipes, etc. Certain basic information must be stored, in order for the system to operate, but other information is elective, and is a function of the particular uses and analysis to which the WSSM is to be put. Other program modules communicate with the data base through standardized data base access methods, which consist of routines to extract or insert information into the network data base.

The two key modules in terms of system evaluation are the hydraulic and solver algorithms. The current version of WSSM uses both WATSIM and the "Wood Model" as the basis for hydraulic analysis. Both of these algorithms are standards available in the profession and are described elsewhere. The second module SOLVER is a general purpose algorithm that sets up and solves problems relating to mixing in networks, given the network topology and flows.[16] It is used with WSSM for three generic types of problems: (1) determining time required to travel from any source to a node (travel time); (2) determining the concentration of any constituent at any node, given the concentration of the constituent at all sources, and (3) determination of the cost of delivered water at any node, given the individual annualized costs associated with the nodes and links of the system. Ultimately a major objective of the model will be to generate spatial cost variations over the utilities service area as shown in Figure 9.

NORTH PENN PROJECT

In order to validate the use of the WSSM as a tool for water quality predicting, EPA is conducting a study with the North Penn Water Utility north of Philadelphia to evaluate this concept. Figure 10 displays average total Trihalomethane (TTHM) concentrations throughout the distribution system. Figures 11 and 12 exhibit daily concentration levels and the variations possible depending on the quality contribution each water source may make or how water is being routed on that day.

NATIONAL BUREAU OF STANDARDS

Research is being conducted in cooperation with the National Bureau of Standards to evaluate hydraulic models and conditions on their use in predicting biofilm establishment and corrosion rates in distribution systems.

Methods will be developed to determine residence times for separated recirculation cavity flow conditions and rate of growth from particulate deposits at obstacles which induce separation and eddy formation.

SUMMARY AND CONCLUSIONS

More attention needs to be paid to the problems associated with both the increased cost of distribution and quality deterioration in drinking water systems due to infrastructure problems. These problems include issues related to economics and public health and their interactions. The majority of pipes in the two systems discussed in this paper have had no maintenance events at all and the vast majority have had no more than two maintenance events. The period from installation to the first event is highly variable, but there are "hot spots" that one should moniter in the utility service area. Once the first event occurs, the period between events becomes increasingly short, and it is important that data be collected in some sort of consistent, understandable, reproductible, and analyzable manner.

From this analysis, justification of replacement of a pipe based on break or event record alone will be difficult. Even with the most dramatic break rate the direct economics of repair barely justify replacement. Other factors should therefore also be considered. For example, loss of capacity in a pipe, customer complaints, and drinking water regulations should be considered in conjunction with maintenance event rates before a replacement decision is made. In addition, the risks associated with a break should be evaluated. If a break is liable to cause severe property damage, the replacement of a given link might be

accelerated and even replaced before it fails. Recently, the water supply industry has recognized the distribution system as more than a conduit for moving water, but a substantial factor in the resultng quality and cost of water reaching the consumer.

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Table 1. INCIDENCE OF WATERBORNE DISEASE

	Distribution Deficiencies		All Cases	
	Outbreaks	Cases	Outbreaks	Cases
1946-1970	59	4,736	356	72,358
1971-1980	43	8,702	320	78,000

Table 2. PERCENTAGE OF COST BY CATEGORY

Item	Support Services	Acquisition	Treatment	Power & Pumping	Transmission & Distribution
Operating Cost	31	22	12	16	19
Capital Cost	10	13	10	--	67

Table 3. SUMMARY STATISTICS FOR CASE STUDY UTILITIES

	Utility 1	Utility 2
Population served	.75 million	.37 million
Number of sources	2	11 wells and 16 reservoirs
Treatment plants	2	2
Maximum capacity	260 MGD	100 MGD
Yearly average	150 MGD	50 MGD
Miles in distribution system	3900	1353
% Cast iron	97.5	97.8
% Reinforced concrete	2.1	1.4
% Steel	0.4	.01

Table 4. COMPARISON BETWEEN DATA SETS AND ACTUAL SYSTEM

Diameter (inches)	Utility 1		Utility 2	
	Data Set (%)	Actual System (%)	Data Set (%)	Actual System (%)
6	1.70	59.85	4.25	18.44
8	6.30	22.34	8.50	48.22
10	0.99	2.17	2.75	4.19
12	10.40	5.60	17.00	13.66
16	18.15	2.64	13.75	6.76
20	4.57	0.66	2.25	2.14
24	23.00	1.95	23.25	1.71
30	5.30	0.45	4.50	0.99
35	0.12	0.02	-	-
36	17.30	1.56	11.50	1.11
40	0.00	0.01	-	-
42	4.00	0.31	4.00	0.11
48	4.28	0.30	7.00	0.91
54	0.75	0.06	0.25	0.01
60	0.90	0.07	-	-
84	1.50	0.11	-	-
96	0.90	0.77	-	-

(-) None in system.

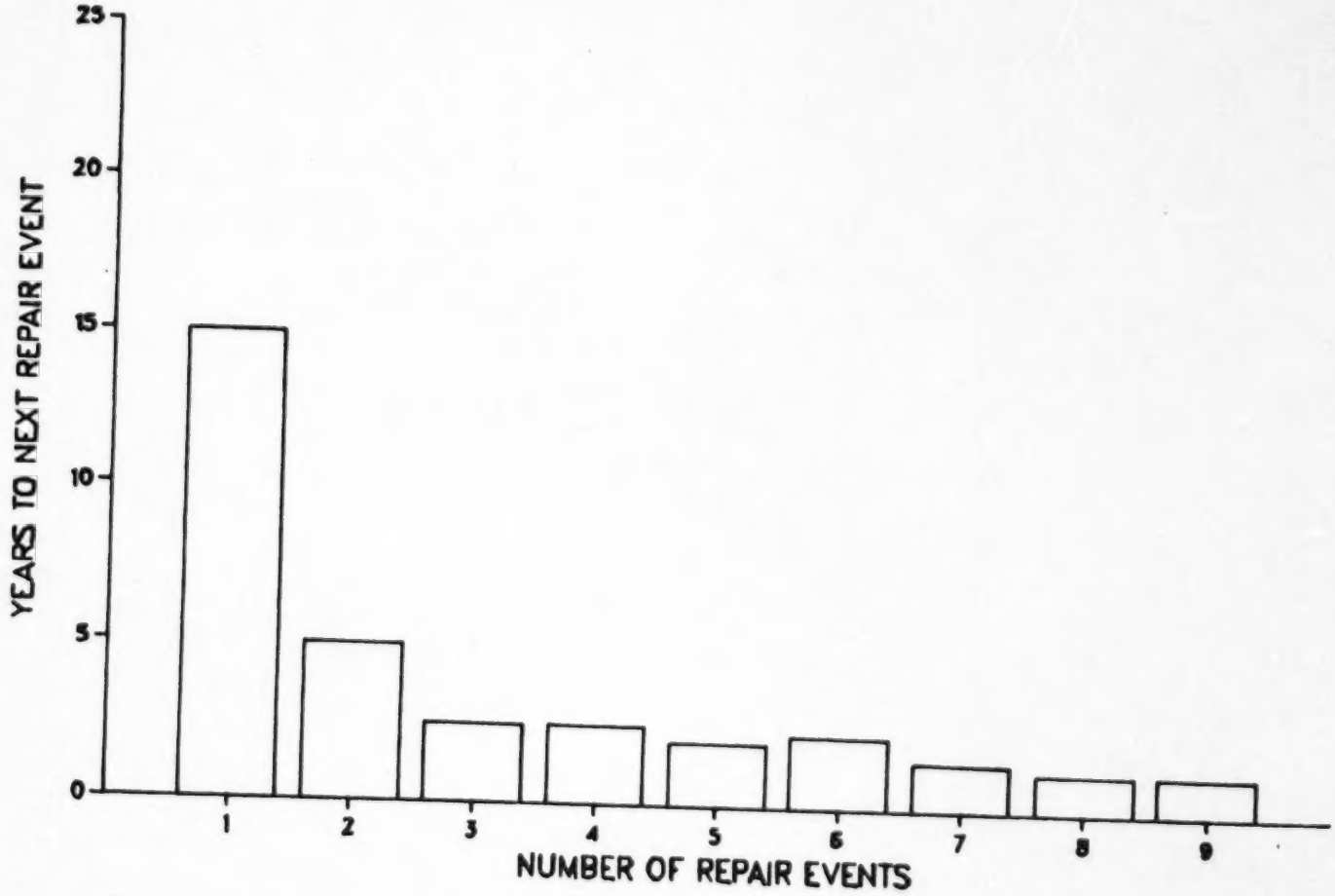

FIGURE 1. AVERAGE NUMBER OF YEARS TO NEXT FAILURE FOR UTILITY 1

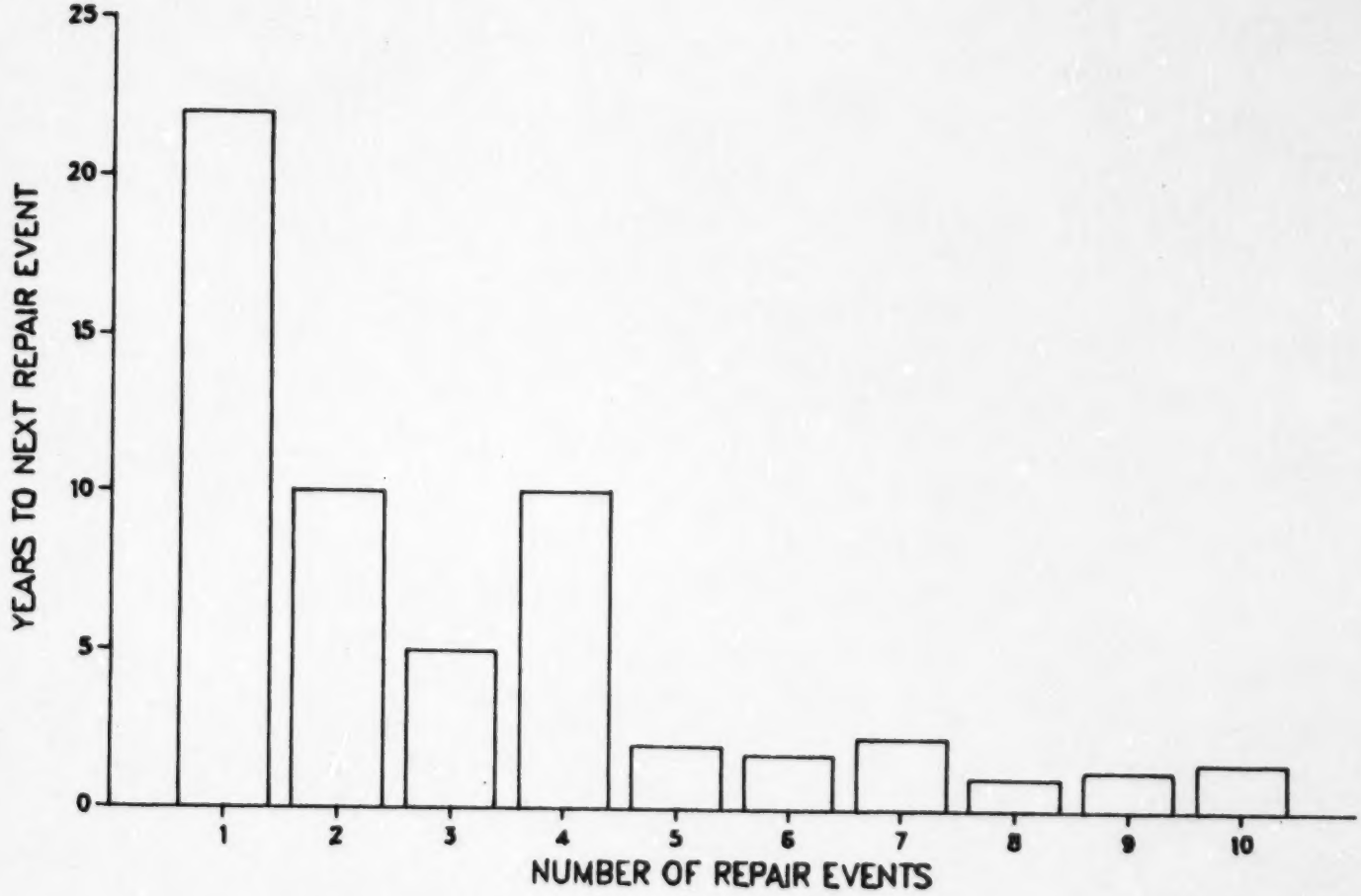

FIGURE 2. AVERAGE NUMBER OF YEARS TO NEXT FAILURE FOR UTILITY 2

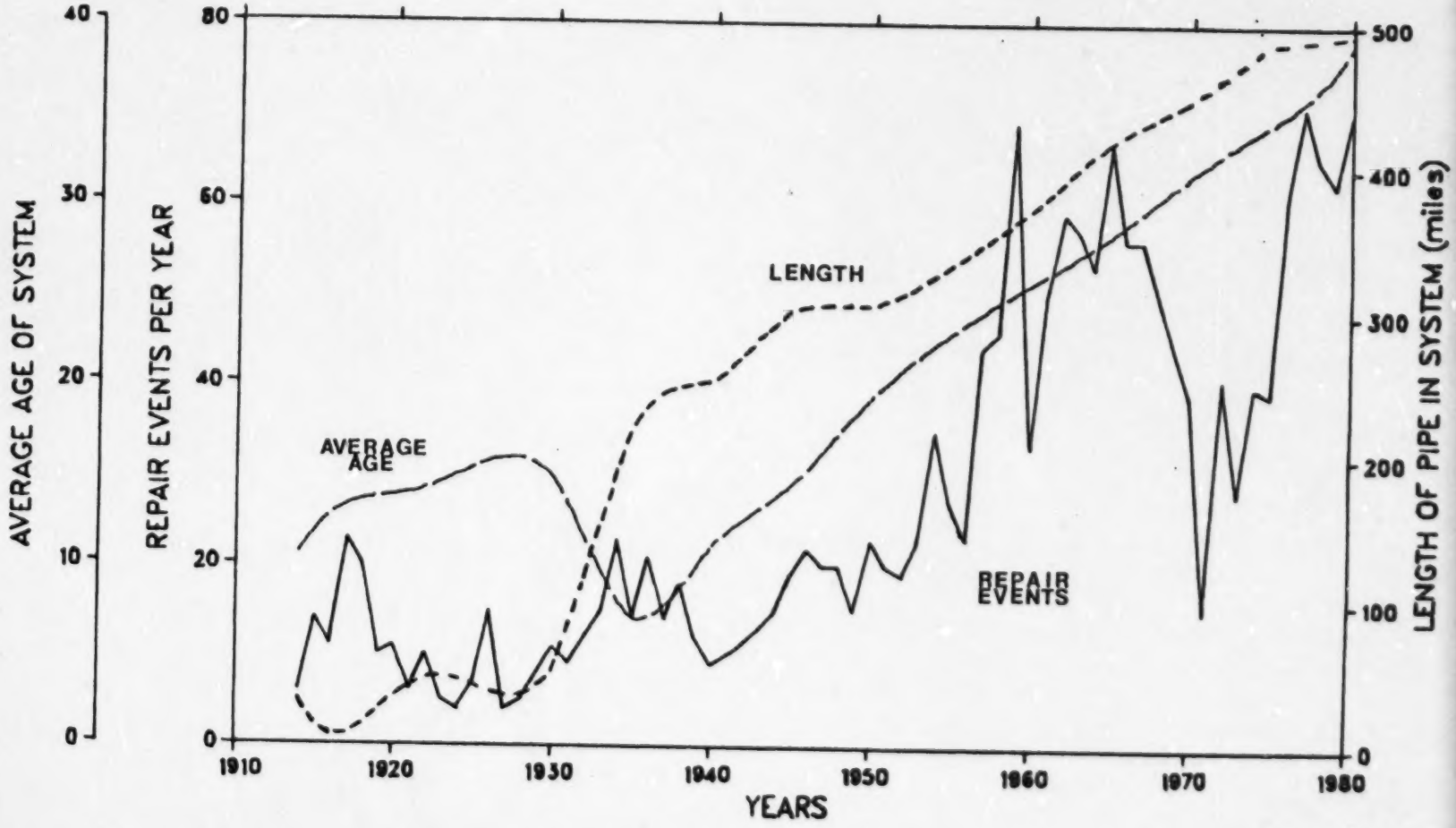

FIGURE 3. REPAIR EVENT HISTORY FOR UTILITY 2

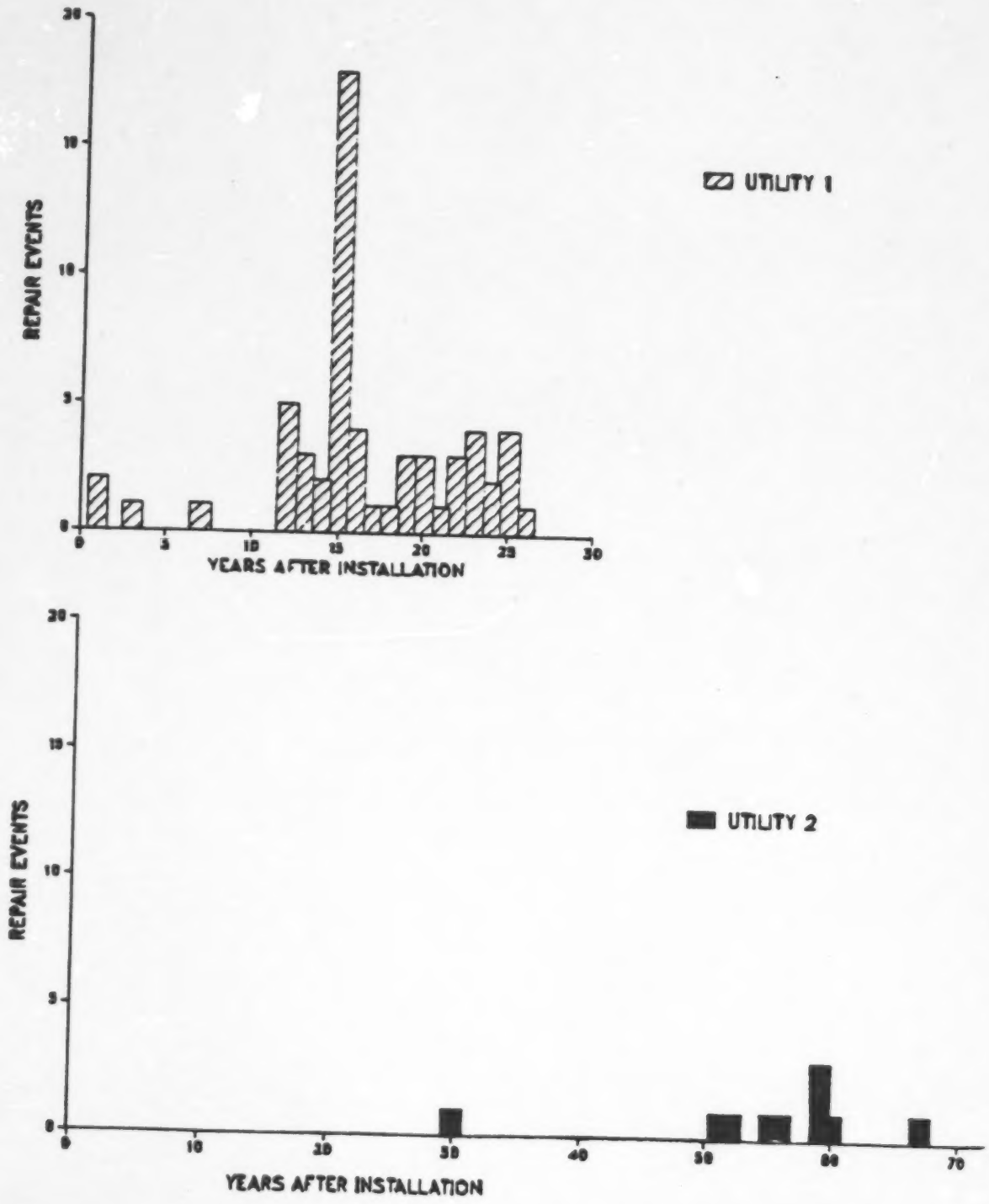

FIGURE 4. BREAKS/YEAR VERSUS YEARS AFTER INSTALLATION FOR BOTH UTILITIES

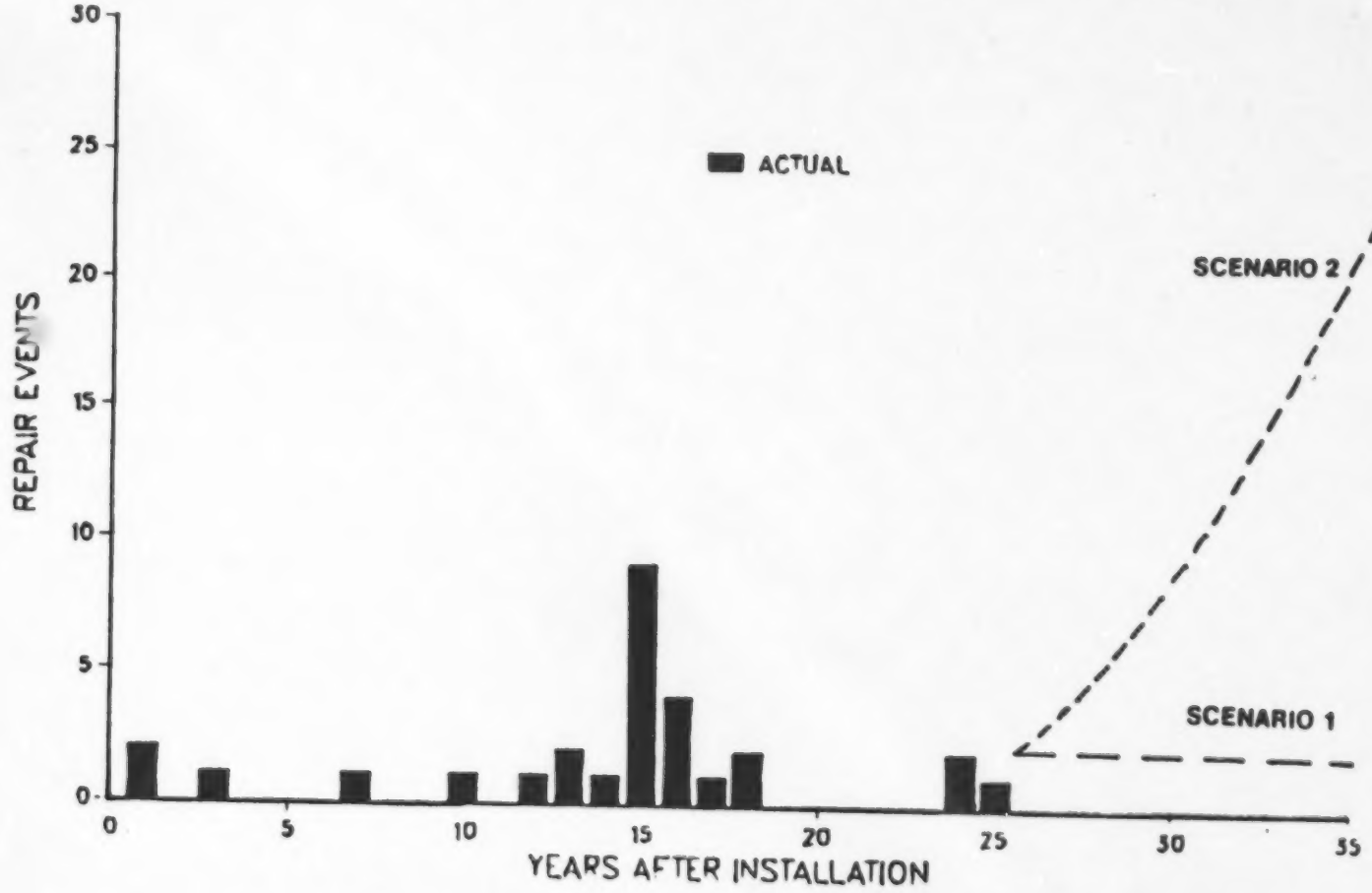

FIGURE 5. MAINTENANCE EVENT SCENARIOS

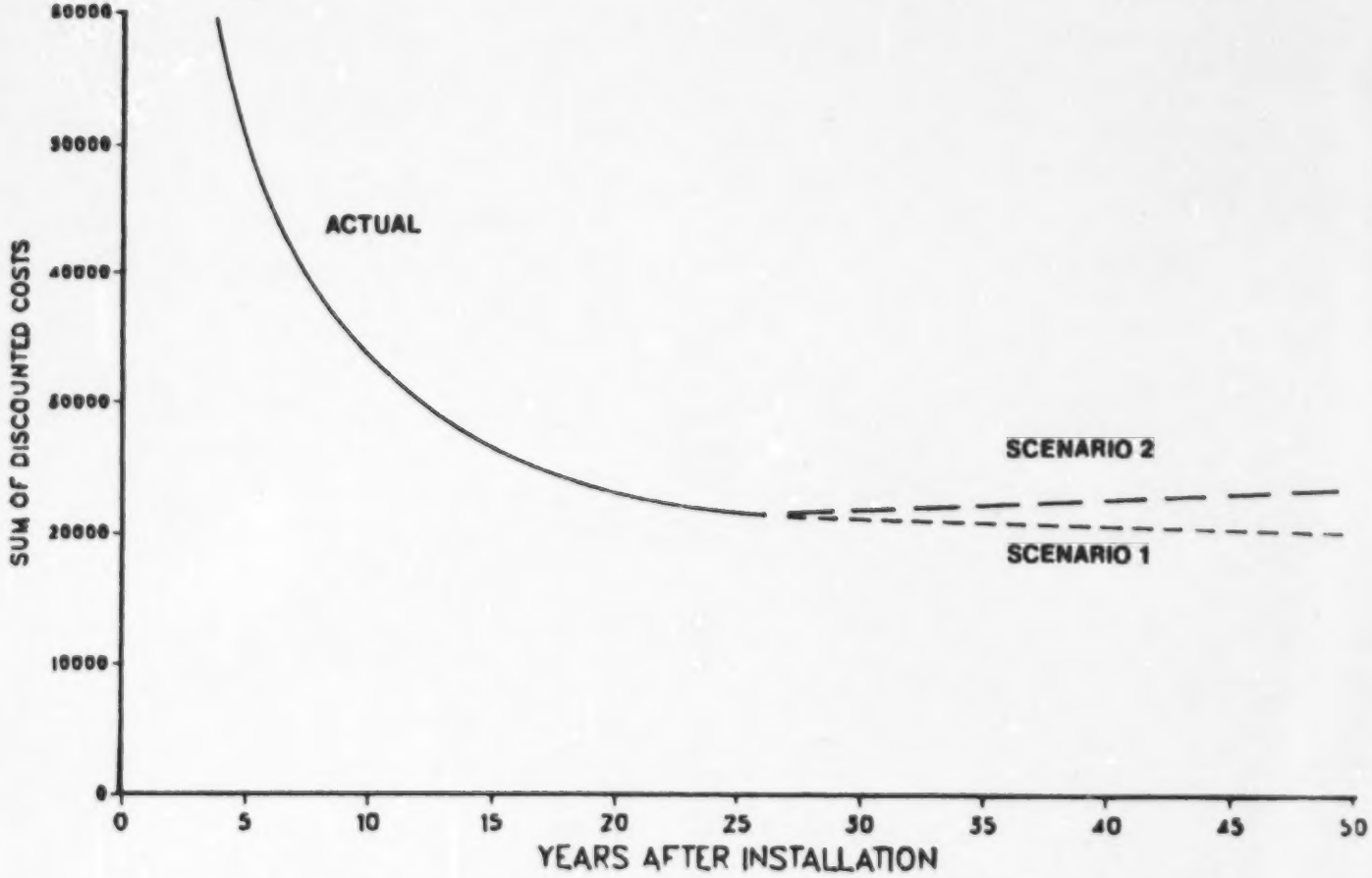

FIGURE 6. AVERAGE WEIGHTED COST VERSUS TIME

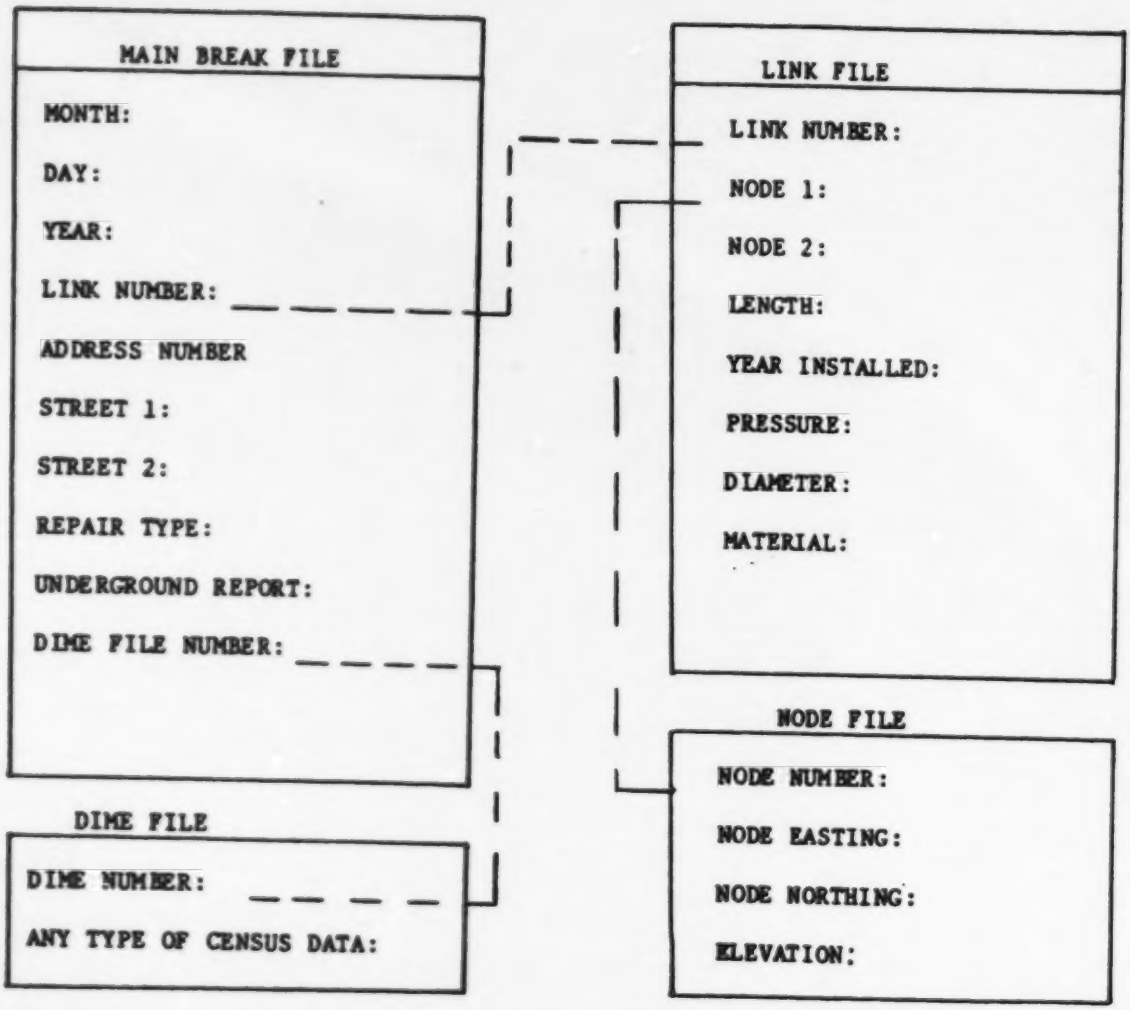

FIGURE 7. RELATIONAL DATA BASE ORGANIZATION

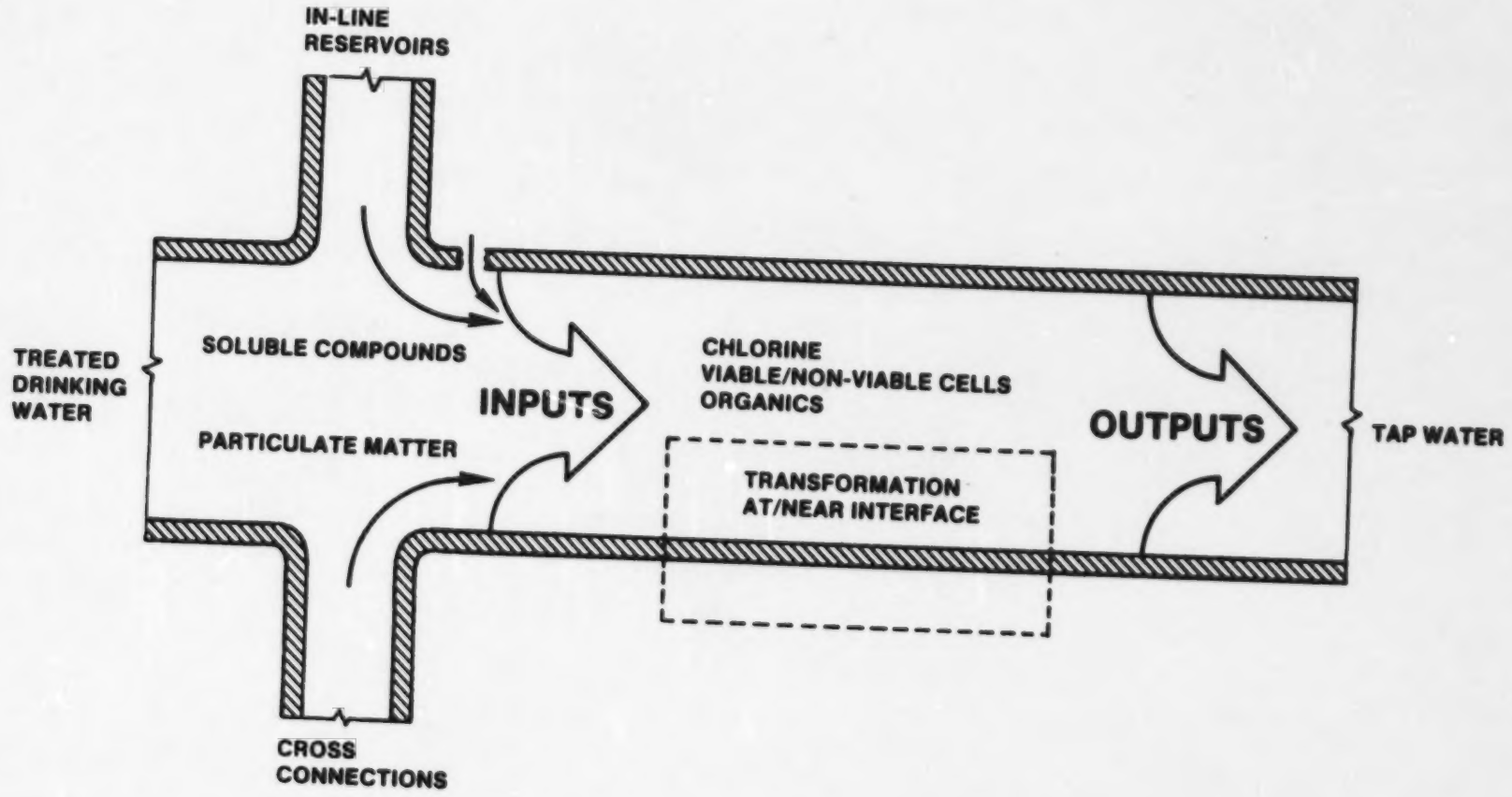

FIGURE 8 WATER DISTRIBUTION PIPE

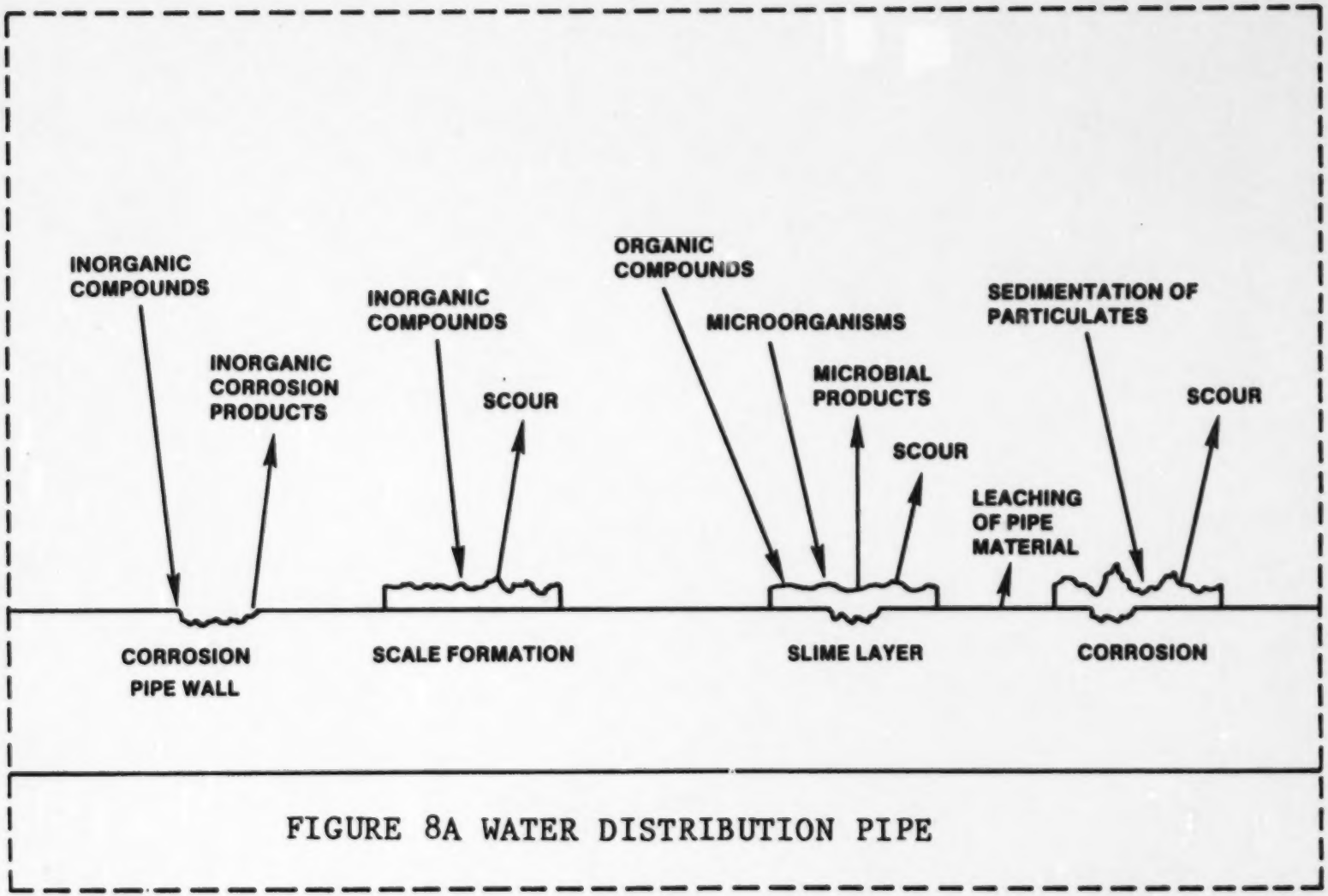

FIGURE 8A WATER DISTRIBUTION PIPE

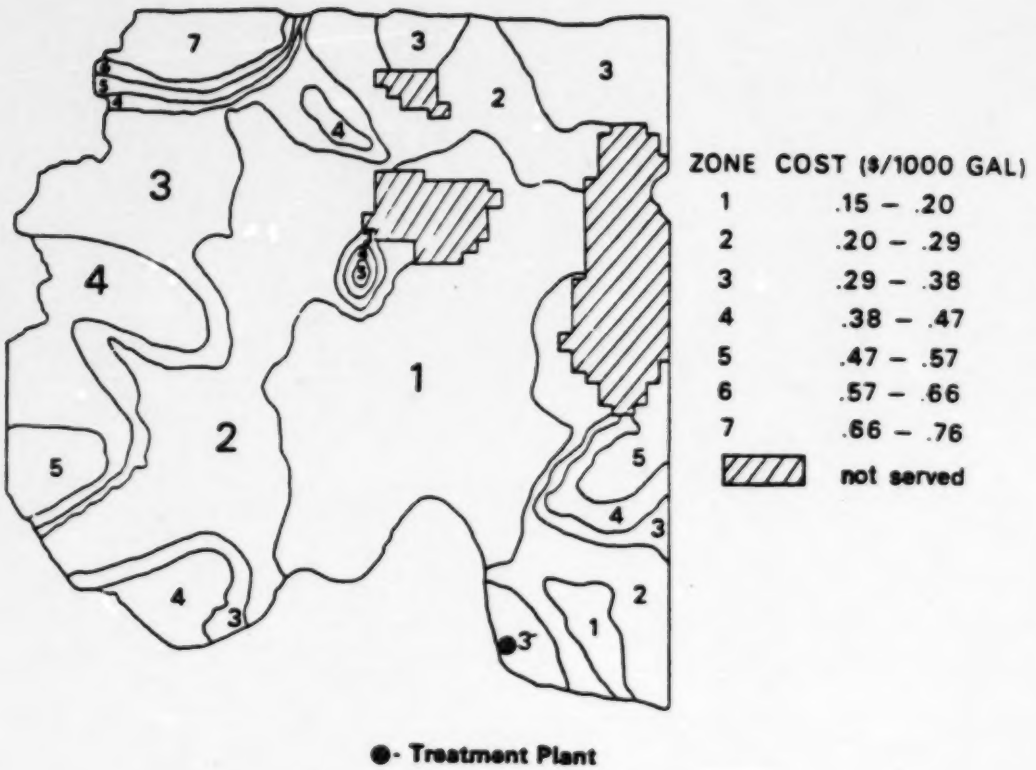

FIGURE 9. COST CONTOUR SIMULATIONS

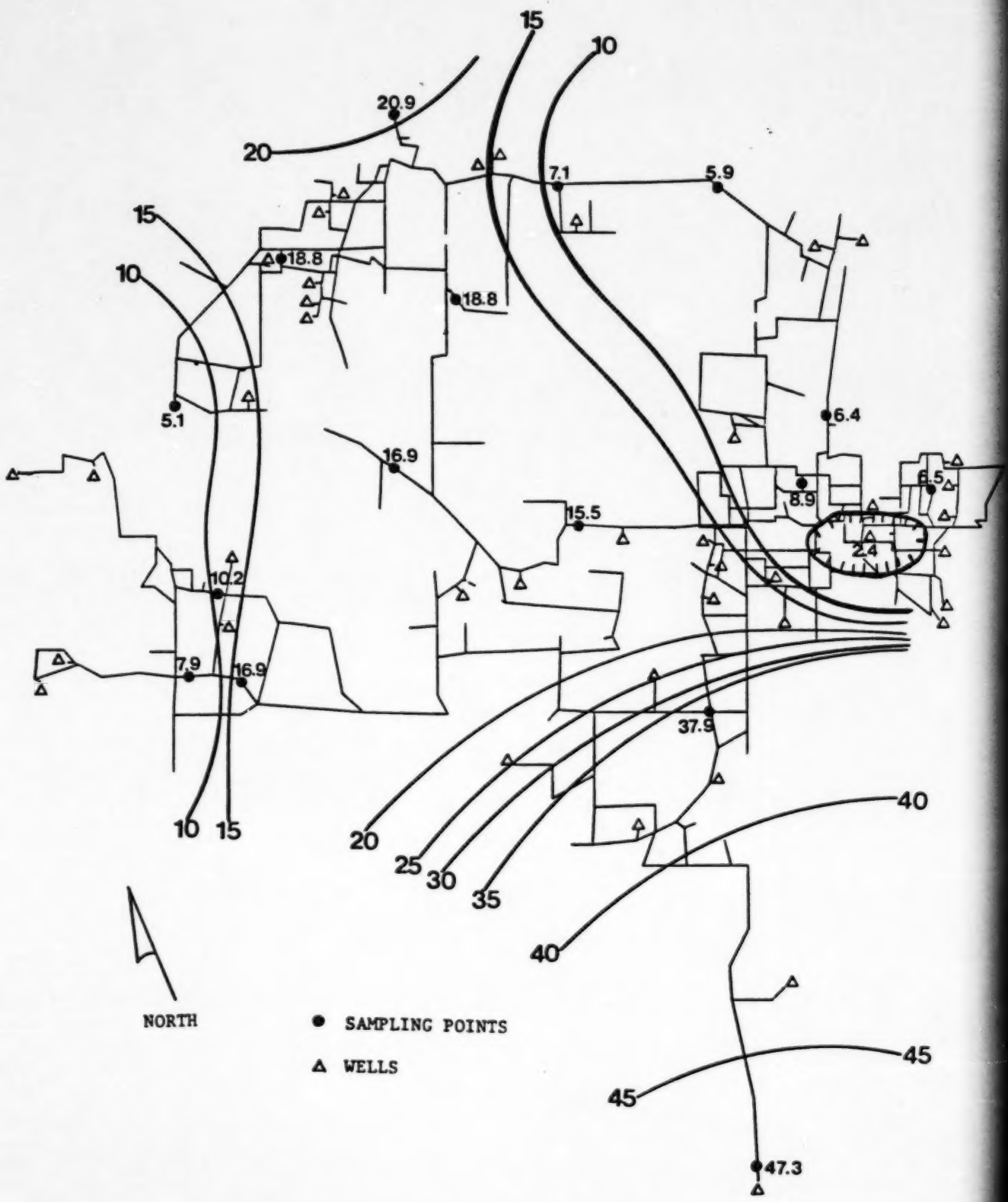

FIGURE 10. AVERAGE TTHM CONCENTRATION CONTOURS (UG/L)

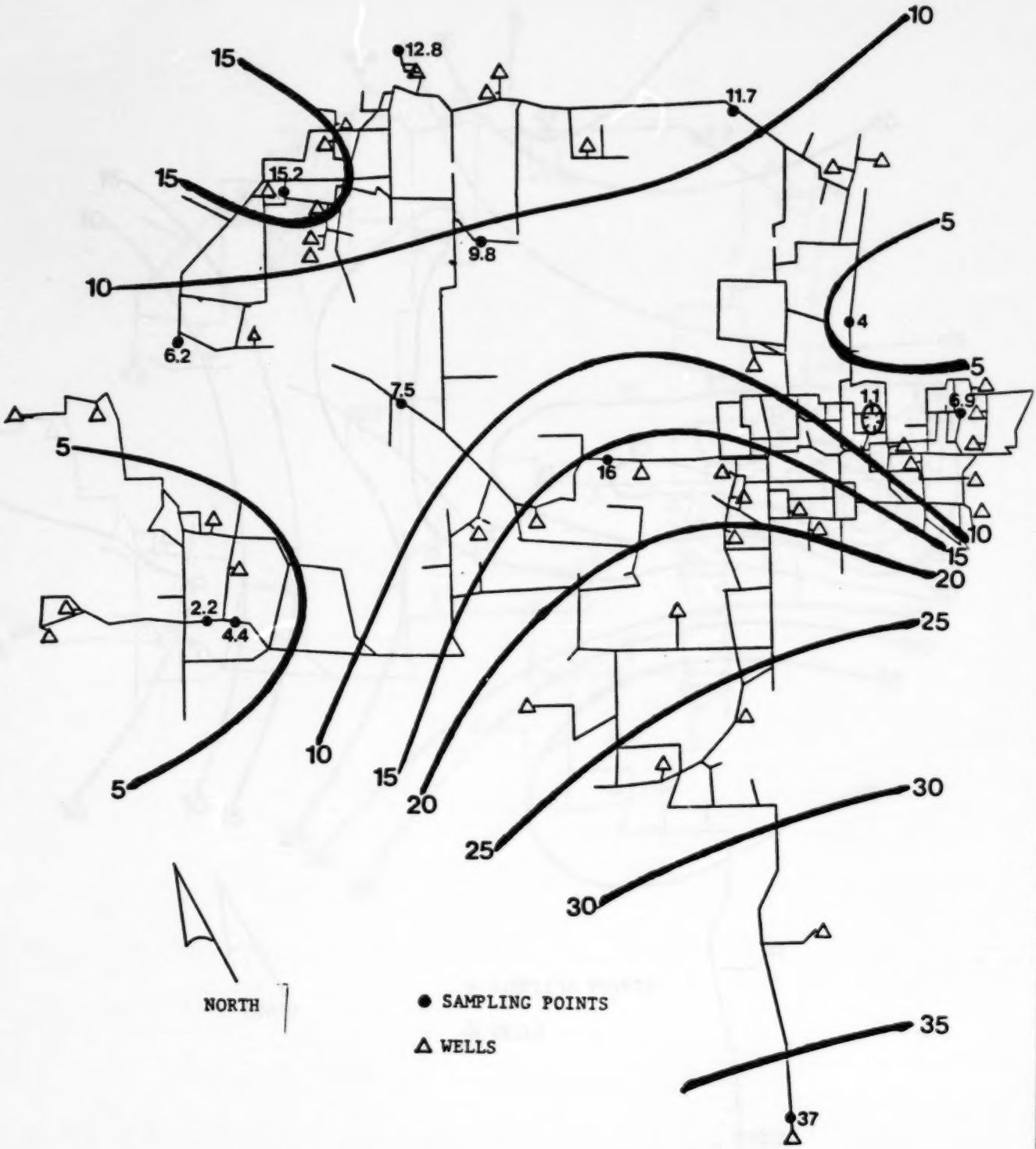

FIGURE 11. DAILY TTHM CONCENTRATION CONTOURS FOR 4-16-84 (UG/L)

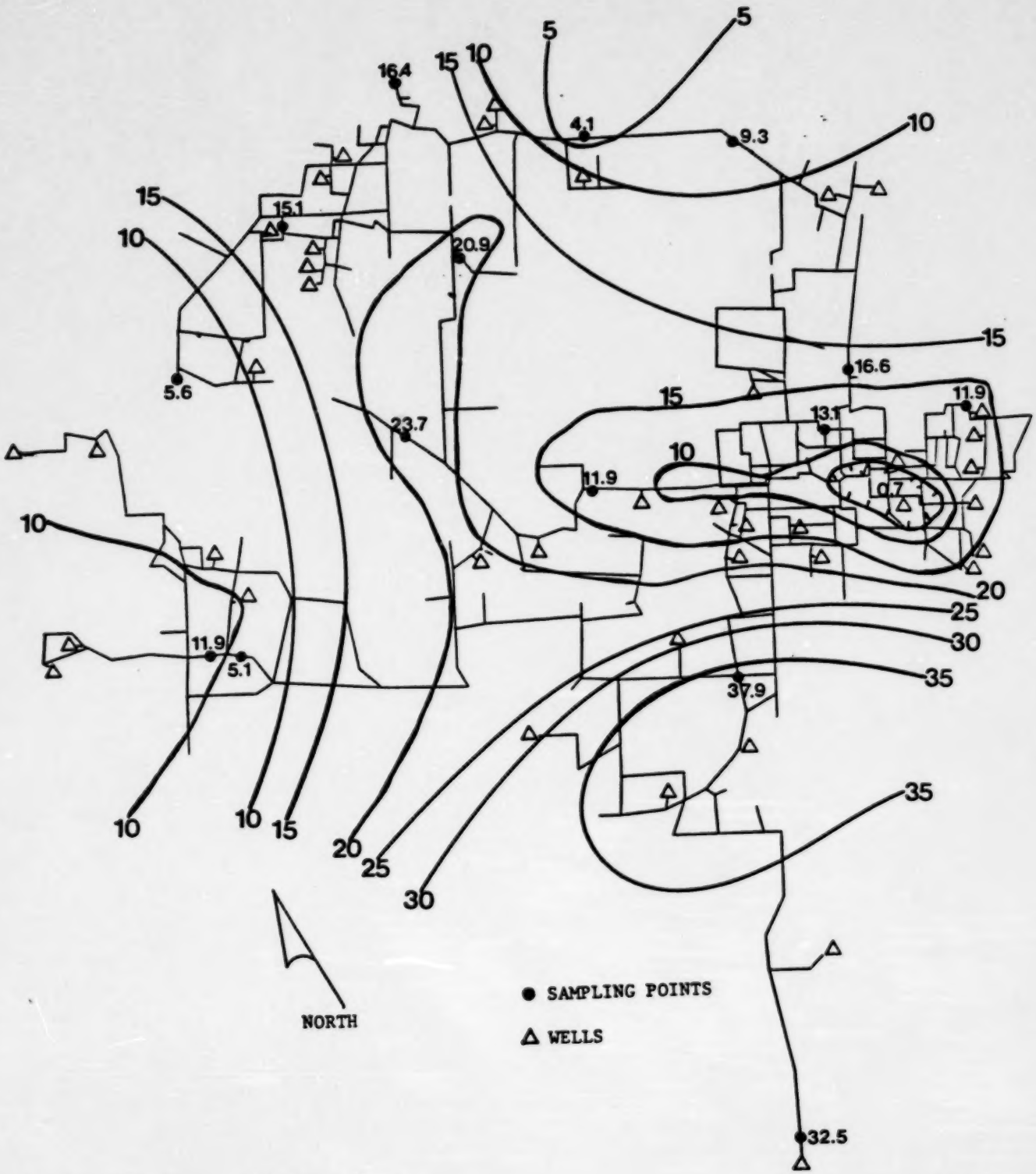

FIGURE 12. DAILY TTHM CONCENTRATION CONTOURS FOR 4-16-85 (UG/L)